American Concrete Institute®
Advancing concrete knowledge

The Art of Designing Ductile Concrete in the Past 50 Years: The Impact of the PCA Book and Mete A. Sozen, Part 2

ACI Fall 2012 Convention
October 21 – 24, Toronto, ON

ACI WEB SESSIONS

Beth Brueggen, Associate III, Wiss, Janney, Elstner Associates, Inc., Irving, TXPrior to joining WJE, Dr. Brueggen worked as a research assistant in the Multi-Axial Subassemblage Testing (MAST) Laboratory at the University of Minnesota. Her work focused on the behavior and seismic detailing of non-rectangular reinforced concrete shear walls under multidirectional lateral loads.

ACI WEB SESSIONS

Simplified Modeling of Non-Rectangular RC Structural Walls

Beth Brueggen – Wiss, Janney, Elstner Associates, Inc.
Cathy French – University of Minnesota

ACI Fall 2012 Convention
October 21, 2012

This research was completed under grant CMS 0324504 from the National Science Foundation.

Proud to be part of the Illinois Mafia

Outline

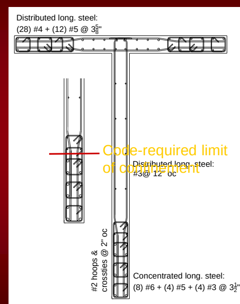
- Introduction
- Simplified Modeling Procedure
  - Load vs. Deflection Relationship
  - Prediction of Damage States
- Validation
- Summary & Recommendations

Specimen NTW1

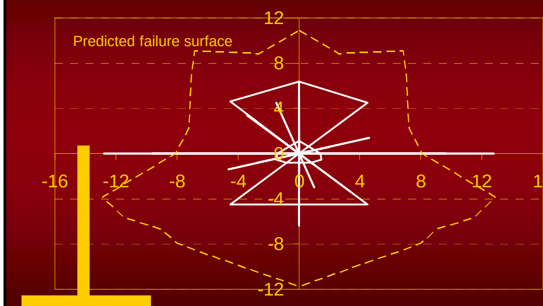
- 4 stories
- Continuous reinforcement over height
- Reinforcement concentrated in boundary elements
- Confinement spacing relaxed from ACI 318-02 (consistent with ACI 318-11)

Specimen NTW2

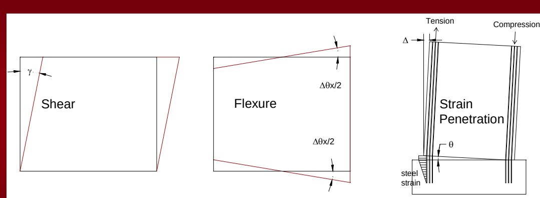
- 2 stories
- Lap splices above first floor level
- Uniformly distributed longitudinal steel in flange
- Expanded confined region



Applied displacements



Deformations of Interest



Performance Level

Operational	Immediate Occupancy	Life Safety	Collapse Prevention

Damage State & Needed Repair

Engineering Limit State

Threshold strain/drift/etc. related to crack size, spalling, crushing, bar buckling or fracture

Existing Modeling Tools

- Simplified Models
  - FEMA 356/ASCE 41 Supplement 1
  - Hines Bridge Pier Model
- Other Models
  - Waugh & Aaletti OpenSees Wall Model
  - Other finite-element-based approaches

Outline

- Introduction
- Simplified Modeling Procedure
  - Load vs. Deflection Relationship
  - Prediction of Damage States
- Validation
- Recommendations

Desired Capabilities of Procedure

- Appropriate for general design use
- More precise than FEMA 356/ASCE 41 Supp. 1
- Applicable to any flexural wall geometry (i.e. rectangular or flanged, height, length)
- Not sensitive to particular detailing (i.e. ρ, distributed or concentrated reinforcement, splices, confinement)
- Applicable to any loading direction, orthogonal or skew
- Transparent procedure, additional terms can be incorporated

WJE MAST

F-S-SP Integration Model

- Based on flexural sectional analysis
- Flexural Component
  - Integrate M-ϕ twice
- Shear Component
  - Calculated from cracked shear stiffness & flexural stiffness
- Strain Penetration Component
  - Calculated from longitudinal strains at base

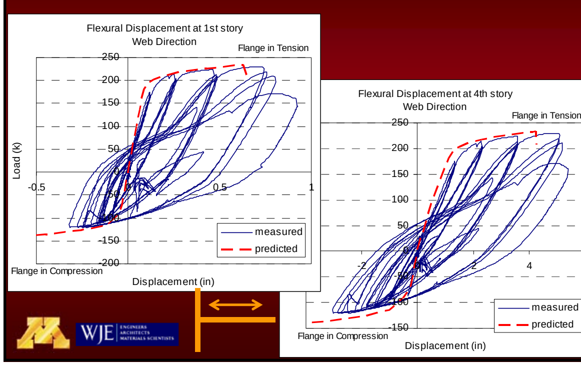
WJE MAST

Flexural Component of Deformation

- Section analysis calculates M-ϕ relationship
- Integrate twice over height of specimen to get P-Δ for flexural deformations
- Assumes plane sections remain plane
  - Neglects shear lag in flanged walls
  - Neglects tension shifting
- Challenges with post-peak behavior

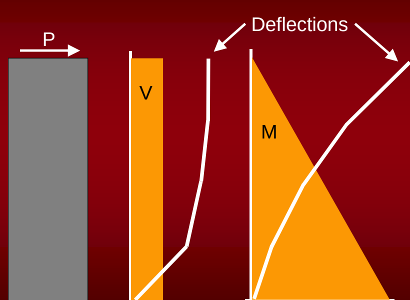
WJE MAST

Effectiveness of Model



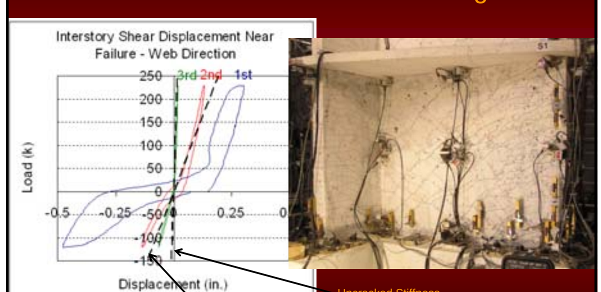
WJE MAST

Shear Demands and Shear Deformation



WJE MAST

Observed Relationship between Shear Deformation and Flexural Damage



$K_v = \frac{\rho_v E_s b_w d}{1 + 4n\rho_v}$

WJE MAST

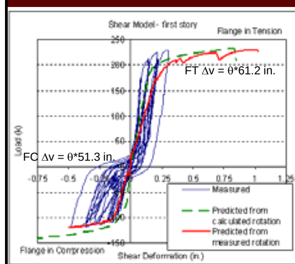
Proposed Method

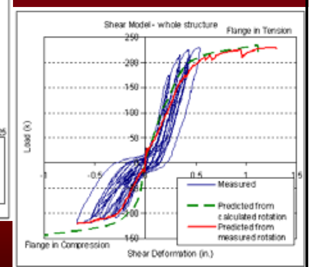
- Δ_v=C*θ_f or γ=C*ϕ
- Use cracked shear stiffness & flexural stiffness at yield to define proportional relationship

$$K_v = \frac{\rho_v E_s b_w d}{1 + 4n\rho_v} \quad \text{for 45° cracks}$$

- $C = \dfrac{M_y / \phi_y}{K_v * z}$ z = shear span

Effectiveness of Model

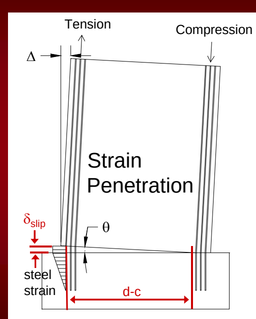




Strain Penetration

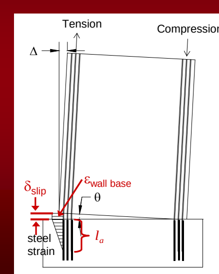
- Assume plane sections remain plane
- Assume behavior in tension and compression similar

$$\theta = \frac{\delta_{slip}}{d - c}$$

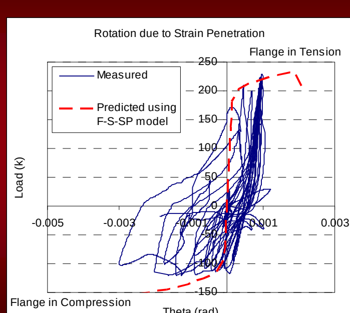


Proposed Method

- Assume constant bond length & strain gradient
- $\delta_{slip} = \frac{1}{2}\varepsilon_{wallbase} * l_a$
- $\boxed{\theta = \frac{\delta_{slip}}{d-c} = \frac{\varepsilon_{wallbase} * l_a}{2(d-c)}}$



Effectiveness of Model



Prediction of Damage Levels

FEMA 356, ATC 58-2, etc. | Berry, Lehman, & Lowes (2008) | NTW1 & NTW2, RW1, RW2, & RW3

Damage	Performance Level	Required Repair	Local EDP	Threshold Value
Negligible		None	Steel tensile strain	$\varepsilon_s<3.5\varepsilon_y$ conc. steel $\varepsilon_s<7\varepsilon_y$ dist. steel
Minimum	Immediate Occupancy	Epoxy injection of cracks	Steel tensile strain	$\varepsilon_s>3.5\varepsilon_y$ conc. steel $\varepsilon_s>7\varepsilon_y$ dist. steel
Minimal		Patching of concrete cover and epoxy injection of cracks	Cover concrete compressive strain	$\varepsilon_c> 2f'_c/E_c$ or 0.003
Moderate	Life Safety	Replacement of concrete cover and epoxy injection of cracks	Core concrete compressive strain	$\varepsilon_c>4kf'_c/E_c$
Significant	Collapse Prevention	Replacement of section		Model indicates post-peak loss of capacity

Outline

- Introduction
- Simplified Modeling Procedure
  - Load vs. Deflection Relationship
  - Prediction of Damage States
- Validation
- Summary & Recommendations

Model Validation

- Comparison to NTW1 & NTW2
- Comparison to results of 6 tests reported in literature
- Comparison to FEMA 356/ASCE 41 Supplement 1 & Hines models
- All validation based on reported as-built material properties
- In general
  - Moment capacity predicted within 5% in all cases
  - Displacement capacity typ. underpredicted 5 to 40%

Sections Used for Validation

- Johnson (2 walls)

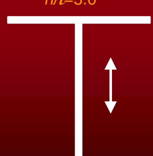
h/ℓ=2.7

- Sittipunt & Wood

h/ℓ=3.0

- Wallace

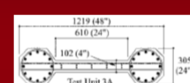
h/ℓ=3.0

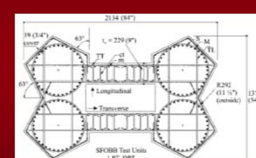


Sections Used for Validation

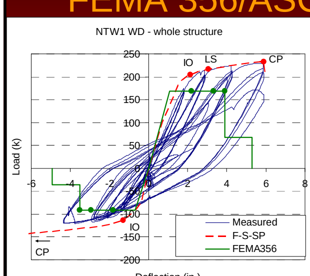
- Hines (2 piers)

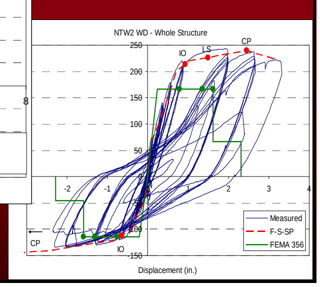
h/ℓ=2.6





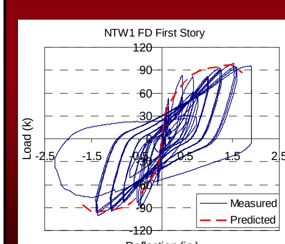
Comparison to FEMA 356/ASCE 41 Supp. 1

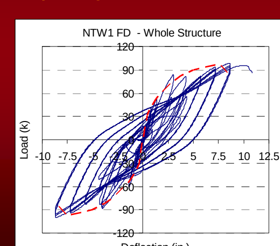




Evaluation of Proposed Model NTW1 Flange Direction

- Load capacity within 3%
- Underestimates drift capacity





Outline

- Introduction
- Simplified Modeling Procedure
  - Load vs. Deflection Relationship
  - Prediction of Damage States
- Validation
- Summary & Recommendations

Summary of Model

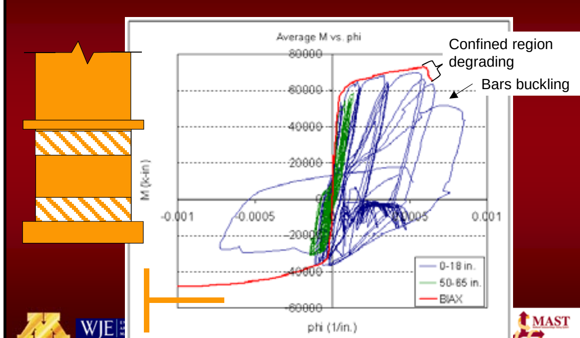
- Takes advantage of relative ease of modeling flexure
- Applicable to more generalized cases than existing simplified tools
- More accurate than existing simplified tools
- Provides framework for predicting damage levels
- Validated using results of tests with aspect ratios of 2.5 to 3.0
- Does not track damage due to prior load history

Possible Modifications to F-S-SP Integration Model

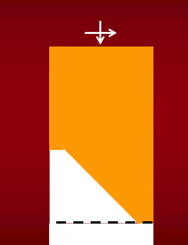
- Calibration of threshold strains for damage prediction using larger data set
- Incorporate shear lag effects
- Add "artificial" plastic hinge length to represent tension shifting
- Improve prediction of post-peak behavior
- Refine shear crack angle prediction
- Refine strain penetration model

Questions?

Measured vs. Predicted Curvature

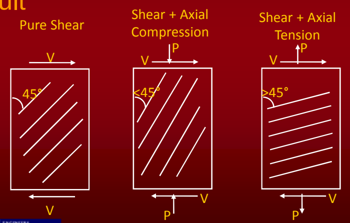


Potential Implications of Neglecting Tension Shifting



Variation in Crack Angle

- General relationships can be established for crack angle; reliable prediction is difficult



Lap Splices Outside Plastic Hinge Region

- Splices in 2nd story did not slip during testing

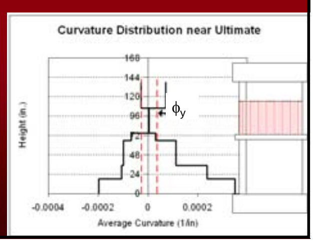
Rectangular wall with lap splices at base

Lap Splices Outside Plastic Hinge Region

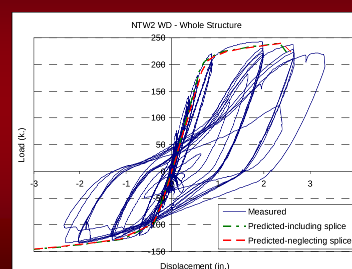
- Splices in 2nd story did not slip during testing
- Lap splices did interrupt yielding
- Neglecting splice increases flexibility ~1-2%

OR

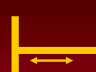
- Use a 2nd model with double steel for lap region



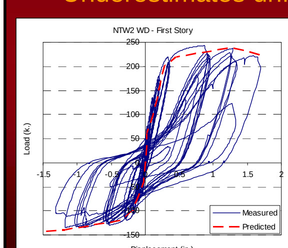
Effectiveness of Flexural Model with Lap Splices

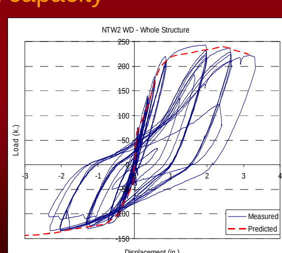


Evaluation of Proposed Model NTW2 Web Direction



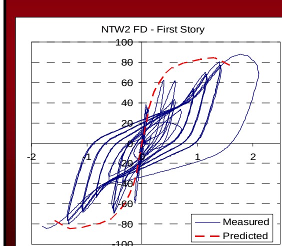
- Load capacity within 0.5%
- Underestimates drift capacity

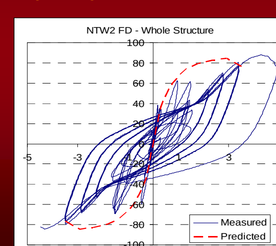




Evaluation of Proposed Model NTW2 Flange Direction

- Load capacity within 3%
- Underestimates drift capacity

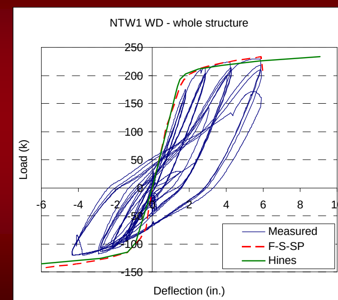




Hines Bridge Pier Model

- Modeling of bridge piers based on sectional analysis
- Limited to cantilevers loaded at tip
- Results only at tip
- Assumes relationship between flexure and shear/strain penetration
- Includes tension shifting term

Comparison to Hines Model

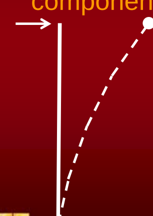


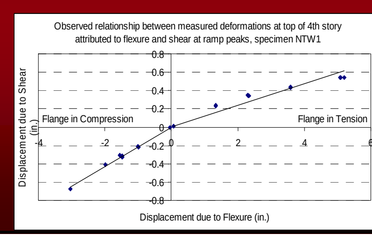
Key Contributions
Performance Based Engineering

- Developed simplified pushover model appropriate for routine design use
- Model separates contributions of flexure, shear, and strain penetration
- Established thresholds linking significant damage levels to local strains

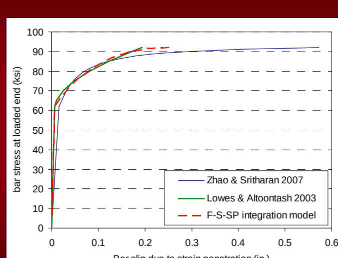
Shear and Flexure Interaction

- Previous researchers have reported a linear relationship between deformation components at tip of specimen

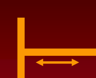




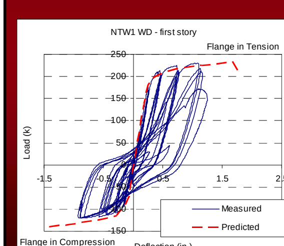
Comparision of Bar Slip Models

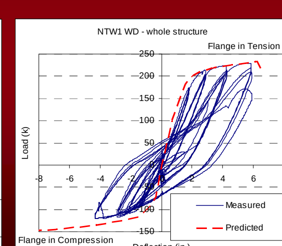


Evaluation of Proposed Model
NTW1 Web Direction



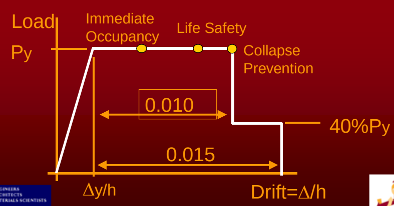
- Load capacity within 2%
- Overestimates drift capacity (exceptional case)





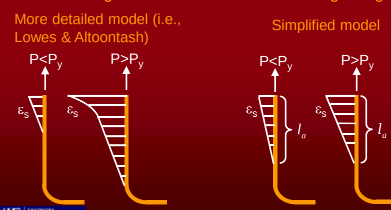
FEMA 356 model

- Modeling of flexure-controlled walls based on elastic flexural stiffness, yield moment, prescribed inelastic drift capacity
- Thought to be very conservative



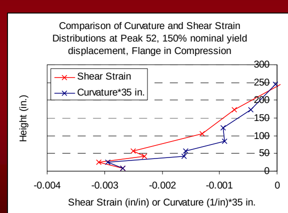
Estimating δ_{slip}

- Bar "slip" is found by integrating strain over anchorage length
- Simplified procedure
  - Assume bond length constant regardless of applied bar stress
  - Assume strain gradient constant over anchorage length



Shear and Flexure Interaction

- Profile of shear deformation similar to profile of rotation over height
- $\gamma = C^*\phi$ or $\Delta_v = C^*\theta_f$



Performance-Based Design